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Shuwei Dai
University of Nebraska-Lincoln, shuwei.dai@huskers.unl.edu

Martha Shulski
University of Nebraska–Lincoln, mshulski3@unl.edu

Kenneth Hubbard
University of Nebraska - Lincoln, khubbard1@unl.edu

Eugene S. Takle
Iowa State University, gstakle@iastate.edu

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A spatiotemporal analysis of Midwest US temperature and precipitation trends during the growing season from 1980 to 2013

Shuwei Dai,[1] Martha D. Shulski,[1] Kenneth G. Hubbard,[1] and Eugene S. Takle [2,3]

1 School of Natural Resources, University of Nebraska-Lincoln, NE, USA
2 Department of Geological and Atmospheric Sciences, Iowa State University, Ames, IA, USA
3 Department of Agronomy, Iowa State University, Ames, IA, USA

Corresponding author — S. Dai, School of Natural Resources, University of Nebraska-Lincoln, 3310 Holdrege Street, Lincoln, NE 68583, USA; email shuwei.dai@huskers.unl.edu

Abstract
Since late 1970s, climate warming has been widely recognized. In the Midwest, farmers cannot rely on the normal calendar anymore, and it has become critically necessary to evaluate the most recent climate trends relative to growing season in order to conduct adaptation efforts for agriculture. Based on the homogenized historical monthly temperature and precipitation records during the period of 1980–2013 from 302 observing stations in the 12 Midwestern US states, we investigate the climate trends on four timescales: monthly, early growing season, late growing season, and the entire growing season. The climate metrics include maximum temperature, minimum temperature, average temperature, diurnal temperature range, and precipitation. Nonparametric Sen's Slope together with the nonparametric Mann–Kendall test is used to estimate the decadal trend and to detect the statistical significance. The results show that growing season average temperature has increased at a rate of 0.15 °C decade^{-1} over the Midwest United States. Within the growing season, minimum temperature is increasing faster in the early growing season, especially in June, while maximum temperature is increasing faster in the late growing season, especially in September. Spatially, statistically significant ($p \leq 0.05$) growing season warming is more focused in the southern part of the region in the early growing season but in the northern part of the region in the late growing season. Over the Midwest, dominant trends in diurnal temperature range are decreasing during most months, with the exception of September. The majority of the locations show increasing trends in growing season precipitation, yet few are statistically significant. Furthermore, precipitation has been increasing in the early growing season but decreasing in the late growing season. This within-season reversing trend in precipitation is found in 8 of 12 Corn Belt states: Illinois, Iowa, Michigan, Minnesota, Missouri, Nebraska, North Dakota, and Wisconsin.

Keywords: Midwest United States, growing season, temperature and precipitation, decadal trends

1. Introduction

Climate change is now one of the greatest challenges facing humanity. Analyses reveal that climate change has indeed started to impact crop production (Hatfield, 2010; Lobell *et al.*, 2011), and the challenges being faced by agriculture relative to climate change are imminent (Hatfield, 2013). Because of climate change, today's farmers are increasingly less able to rely on historical climate 'norms' or calendar dates for making agronomic decisions (Wolfe, 2013; Takle *et al.*, 2014). The positive effects of climate change (such as longer growing season, better soil moisture recharge, and increased atmospheric CO_2) and technology on agricultural productivity may be partially or totally offset by the negative impacts because of the higher temperatures shortening grain-fill duration and increasing evapotranspiration rates (Adams *et al.*, 1990; Lobell *et al.*, 2011). Climate warming has been observed in many parts of the world (Field *et al.*, 2012), resulting in higher risks of crop failure (Wolfe, 2013). The impacts of climate change on agriculture will not be equal across regions, which can be attributed in part to regional variation in the nature and magnitude of climate change impacts, but also variability in farmer recognition that a climate change signal plays a role (Fischer *et al.*, 2005; Adger *et al.*, 2007; Easterling *et al.*, 2007; Lobell *et al.*, 2008). Increased attention has been given to temperature impacts on crop yields in recent years (Schlenker and Roberts, 2009; Lobell *et al.*, 2011), and this has induced a greater sense of urgency to understand the impacts of past climate on crop production and to develop a more robust observational framework for the assessment of agricultural impacts in the United States (Hatfield, 2013). Longer growing seasons increase the number of insect generations per year, warmer winters lead to larger spring populations of marginally overwintering species, and earlier springs lead to the earlier arrival of migratory insects and birds (Wolfe *et al.*, 2008; Hatfield *et al.*, 2011; Courtier *et al.*, 2013).

Observations from 1951 to 2010 confirmed the continuing declines in the number of frost days and increases in thermal time in the western half of the North America (Terando *et al.*, 2012). In the Great Plains region, 2012 was warmest on record at locations over the six states (Colorado Springs, CO; Topeka, KS; Valentine, NE; Fargo, ND; Rapid City, SD; Cheyenne, WY) and driest on record in Nebraska (Grand Island, and Scottsbluff) (Umphlett, 2012). Reduction in snow pack and earlier snow melt in the western United States will exacerbate the potential threat of drought for farmers because reduced runoff will result in a reduction in the water stored in reservoirs for irrigation (Lettenmaier *et al.*, 2008). In the Platte River Basin in central Nebraska, the recent warming trend (1980–2000) is much stronger than during the Dust Bowl era (1930s), especially for the minimum values of daily maximum and minimum temperatures (Irmak *et al.*, 2012).

Trends in temperature variables such as maximum, minimum and average temperatures, and diurnal temperature range will have impacts on crop production. Lobell and Burke (2008) concluded that progress in understanding the magnitude of regional temperature changes is one of the most important needs for climate change impact assessments and adaptation efforts for agriculture. Monthly, seasonal, and interseasonal information is used for production decisions during the growing season, and multiyear or decadal information is used for long-term decisions (Takle *et al.*, 2014). The overall goal of our work is to document the characteristics of trends in maximum, minimum, and average temperatures, diurnal temperature range, as well as precipitation in the Midwest United States for the most recent climatological time period. This would lead to a better understanding of how past climate has been changing in the heartland of corn and soybean production, and to offer scientific support for agricultural adaptation policies or agricultural adaptive management improvement.

2. Data and methods

In this study, the research area includes the 12 Midwestern US states where the national corn and soybean production is concentrated: Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, Ohio, South Dakota, North Dakota, and Wisconsin (USDA and NASS, 2009). In this article, we will refer to this specific region as the Midwest United States. Monthly temperature (including maximum, minimum, and average temperatures) and precipitation data for the Midwest US stations were compiled from the United States Historical Climatology Network (USHCN) Version 2.5 Serial Monthly Dataset (Menne *et al.*, 2014). During the period of 1980–2013, the maximum number of days with missing data allowable for our analyses is set as 9 to incorporate as many stations as possible. A total of 302 observing stations (36.17° –48.97°N and 80.82° –103.63°W, Figure 1) were chosen for the spatiotemporal analysis of temperature and precipitation trends, and the elevation of these stations ranges from 82.3 to 1435.0m. Specifically, the number of observing stations for the trend analysis in precipitation, maximum temperature, minimum temperature, and average temperature is 181, 264, 215, and 186, respectively. Diurnal temperature range is calculated as (maximum temperature − minimum temperature), and the amount of stations used for trend analysis is the same as average temperature. We calculate the mean temperatures (maximum, minimum, and average temperatures, as well as diurnal temperature range) and total precipitation during the early season, late season, and growing season based on the monthly data. In this study, we refer to April through October as growing season, although these months may not be representative for all locations across the 12-state region. The growing season is further divided into two components, early season—corresponding to the vegetative phase of crops (such as corn)—and late season—corresponding to the reproductive phase of crops. The time periods are April to June for the early season and July to October for the late season.

A nonparametric method, Sen's Nonparametric Estimator of Slope, is used in determining the presence of decadal slope (Brauner, 1997). And the nonparametric Mann–Kendall test is used to detect significance levels of the decadal Sen's slopes in temperature and precipitation metrics (Burkey, 2006). This nonparametric test has been widely used in detecting temporal trends in large data sets (Libiseller and Grimvall, 2002). And the combination of Sen's Slope and Mann–Kendall test has been used in evaluating climate variations and trends (e.g. Irannezhad *et al.*, 2014; Nguyen *et al.*, 2014).

3. Results and discussion

3.1. Trends in maximum, and minimum temperatures

Over our study area, the composite trends for growing season maximum and minimum temperatures during the period of 1980–2013 are 0.13 and 0.17 °C decade^{-1}, respectively. During the growing season, statistically significant ($p \leq 0.05$, herein unless otherwise specified) increasing trends in maximum temperature have been detected in the southern part of the region in the early season and in the northern part of the region in the late season (Figure 2(a) and (b)). It is worth noting that dominant trends for maximum temperature in the early season are decreasing in the northwestern part of the region. In addition, there are a greater number of stations demonstrating statistically significant warming in maximum temperature in the late season than in the early season. Therefore, the composite warming trend in the maximum temperature is smaller in the early season than in the late season (Table 1). Within the growing season, statistically significant increasing trends in minimum temperature are concentrated in the southeastern part of the region in the early season, but in the northwestern part of the region in the late season (Figure 2(c) and (d)). On a monthly basis, dominant

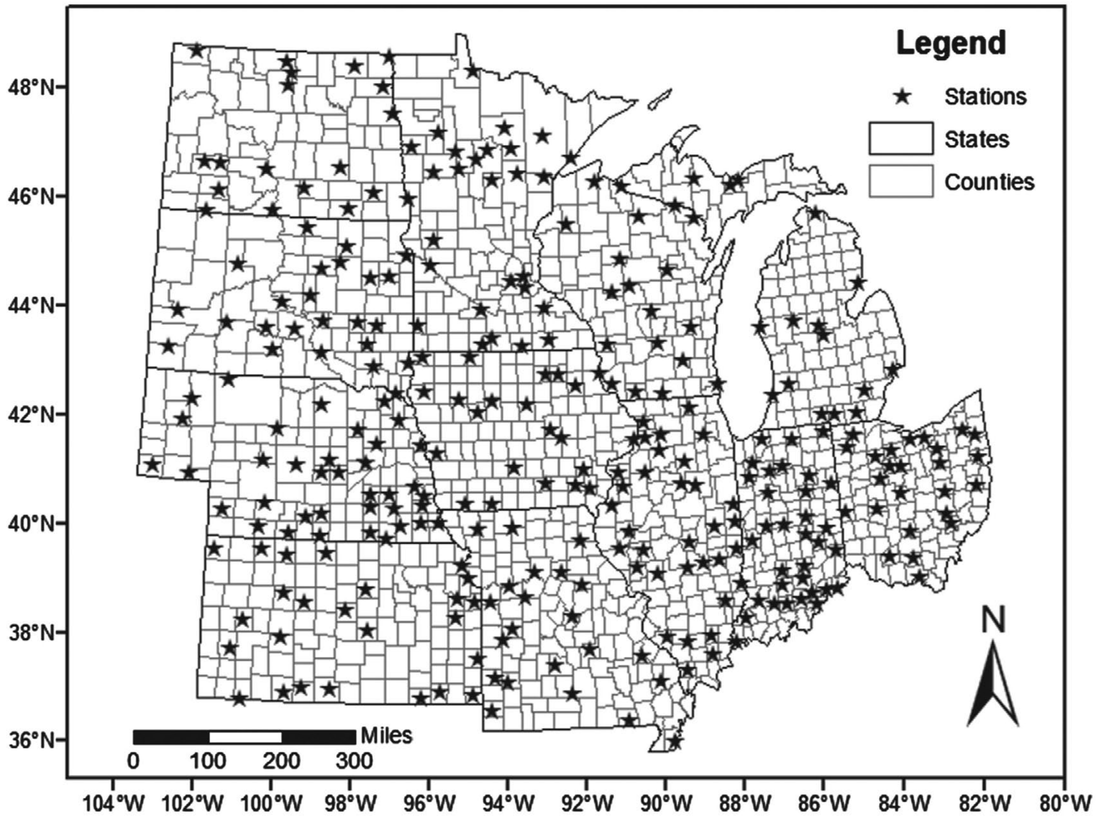

Figure 1. Locations of the 302 meteorological stations in the 12 Midwestern US states.

trends for maximum temperature show an increase, with an exception in July (Table 1). During July, more than half of the locations show decreasing trends in maximum temperature, but few are statistically significant. Feng and Hu (2004) identified a substantial decrease in summer maximum temperature in western Missouri, Illinois, Indiana, and Ohio area during 1951–2000. In this study, we find a subregional cooling trend in July maximum temperature in the southeast part of the research region during 1980–2013. Over the period of 1900s–2009, July and August were found to be the months with the greatest decreases in maximum temperature for the central part of Nebraska (Skaggs and Irmak, 2012). Overall, maximum temperature has the greatest magnitude of warming in September, especially in the northern part of the region (Figure 3(b)). Dominant trends for monthly minimum temperature show an increase for all seven growing months (Table 1). In particular, the composite warming trend in June minimum temperature has the greatest magnitude, when increasing trends occur throughout the study area (Figure 3(a)).

3.2. Trends in average temperature and diurnal temperature range

Since 1980, growing season average temperature has increased by 0.15 °C decade^{-1} on an average in the Midwest United States, and a total of 90% of the research locations shows increasing trends (12% are statistically significant, and they are scattered in the southern and eastern parts of the region). The magnitude in growing season average temperature trend over the Midwest United States covering the period 1980 through 2013, calculated only for the stations with statistically significant trends identified by the Mann–Kendall test, is 0.33±0.06 °C decade^{-1}. This compares with trends of 0.09±0.07 °C decade^{-1} and 0.33 °C decade^{-1} in mean annual temperature over the contiguous United States for the periods 1898 through 2008 (Capparelli *et al.*, 2013) and 1979 through 2008 (Vose *et al.*, 2012), respectively. The regional warming trend in the Midwest is more driven by the increase in growing season minimum temperature than by that in growing season maximum temperature. Within the growing season, statistically significant warming in average temperature is focused in Indiana, Ohio, Illinois, and Missouri in the early season (a total of 22% of the locations), and in Minnesota, Wisconsin, and Michigan in the late season (a total of 23% of the locations). Over the 12 Midwestern states, average temperature is increasing faster in the late season than in the early season (Figure 4). In the early season, dominant trends in average temperature are cooling in North Dakota, South Dakota, and Minnesota (Figure 4), owing to a decrease in maximum temperature for this area. Over the entire Midwest, however, average temperature is uniformly increasing in the seven growing months (Table 1). The greatest warming rate in average temperature occurs in September, when statistically significant warming trends are detected in North Dakota, Minnesota, and Wisconsin (18% of the locations).

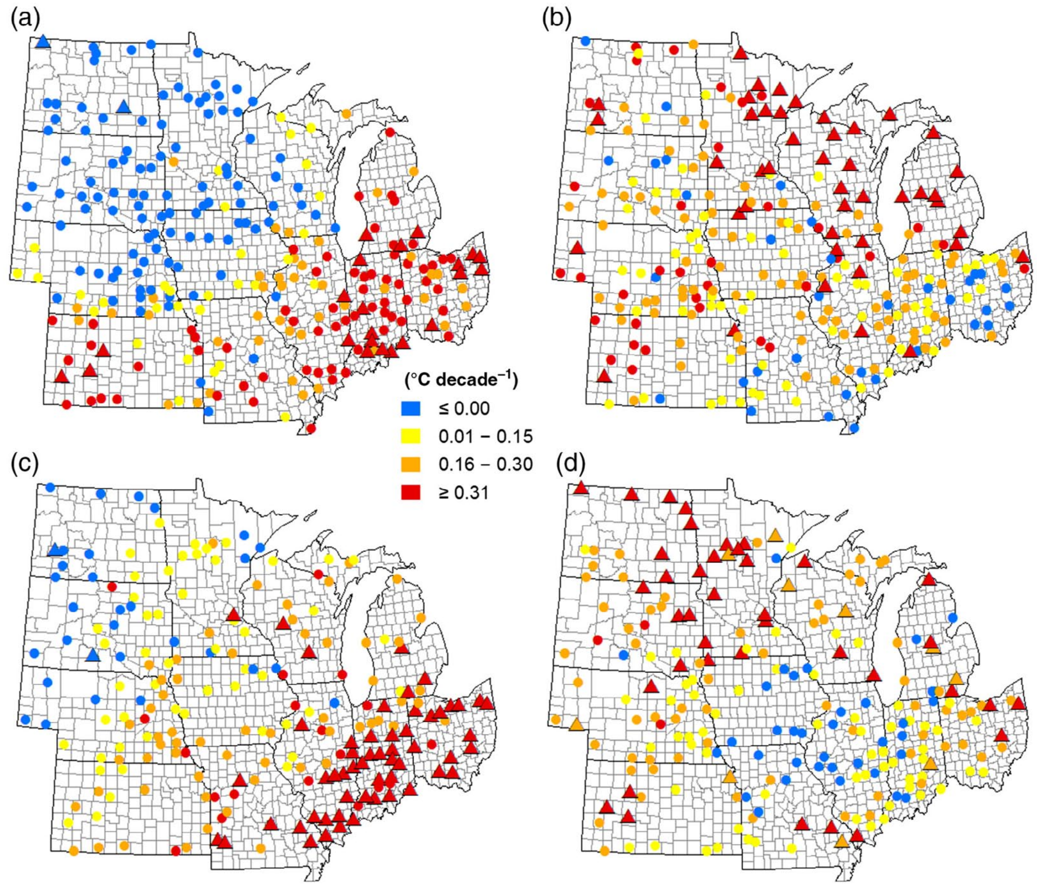

Figure 2. Geographical distribution of the decadal trends in maximum and minimum temperatures during the early season and late season for the period of 1980–2013 for the locations of this study. Note: Circle symbol indicates statistically not significant (p>0.05) trend, and triangle symbol indicates statistically significant (p≤0.05) trend. These definitions are also used in the remaining maps. (a) Early season maximum temperature. (b) Late season maximum temperature. (c) Early season minimum temperature. (d) Late season minimum temperature.

Table 1. Composite trends in maximum, minimum, and average temperatures as well as diurnal temperature range on monthly, early season (ES), and late season (LS) timescales from 1980 to 2013 for the locations of this study (unit: °C decade^{-1}, trends for the early season and late season timescales are set in italics).

Timescale	Trend in T_{max}	Trend in T_{min}	Trend in T_{avg}	Trend in DTR
April	0.15±0.43	0.20±0.24	0.20±0.32	−0.03±0.35
May	0.01±0.43	0.15±0.31	0.09±0.35	−0.08±0.35
June	0.07±0.31	0.28±0.18	0.17±0.20	−0.21±0.29
ES	*0.08±0.33*	*0.21±0.20*	*0.14±0.25*	*−0.08±0.27*
July	−0.02±0.25	0.12±0.22	0.05±0.20	−0.12±0.25
August	0.19±0.20	0.13±0.18	0.15±0.13	−0.01±0.27
September	0.34±0.34	0.18±0.25	0.24±0.26	0.13±0.30
October	0.27±0.26	0.19±0.23	0.21±0.20	−0.06±0.24
LS	*0.21±0.19*	*0.17 ±0.17*	*0.18±0.13*	*0.00±0.22*

From 1980 to 2013, dominant trends in growing season diurnal temperature range (DTR) are negative with a composite trend of −0.04 °C decade^{-1}. More than half of the locations show decreasing trends in growing season DTR, and 13% are statistically significant (they are scattered throughout the region). Within the growing season, the majority of the locations show decreasing trends in DTR both in the early season and in the late season. However, DTR is decreasing faster in the early season than in the late season (Table 1). On the monthly timescale, the dominant trend in DTR is a decrease in all months except September. In September, DTR has been increasing because maximum temperature has increased nearly twice as fast as minimum temperature during the period of 1980–2013. The percentage of locations that show decreasing trends in monthly DTR is 55% in April, 66% in May, 79% in June, 74% in July, 58% in August, and 62% in October. The greatest decreasing magnitude in DTR occurs in June, when minimum temperature has increased four times as fast as maximum temperature.

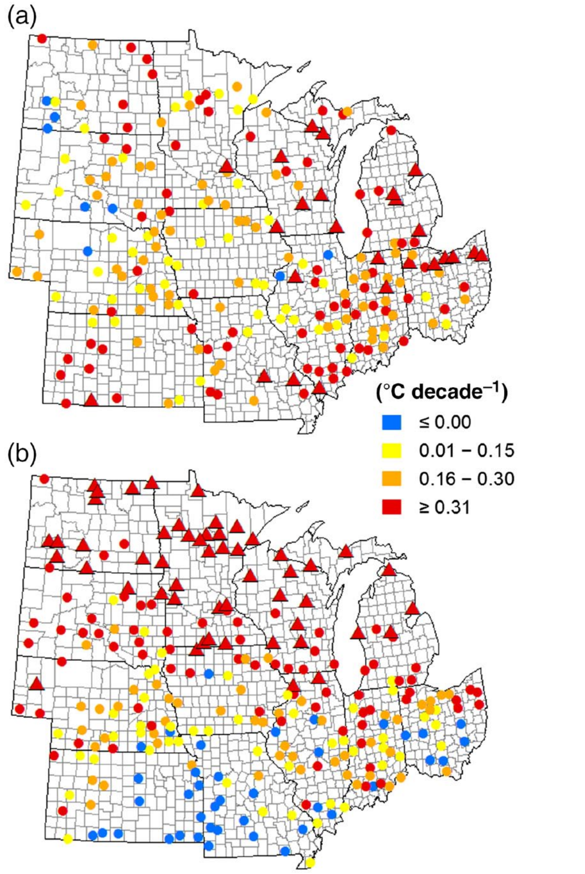

Figure 3. Geographical distribution of the decadal trends in (a) June minimum temperature and (b) September maximum temperature from 1980 to 2013 for the locations of this study.

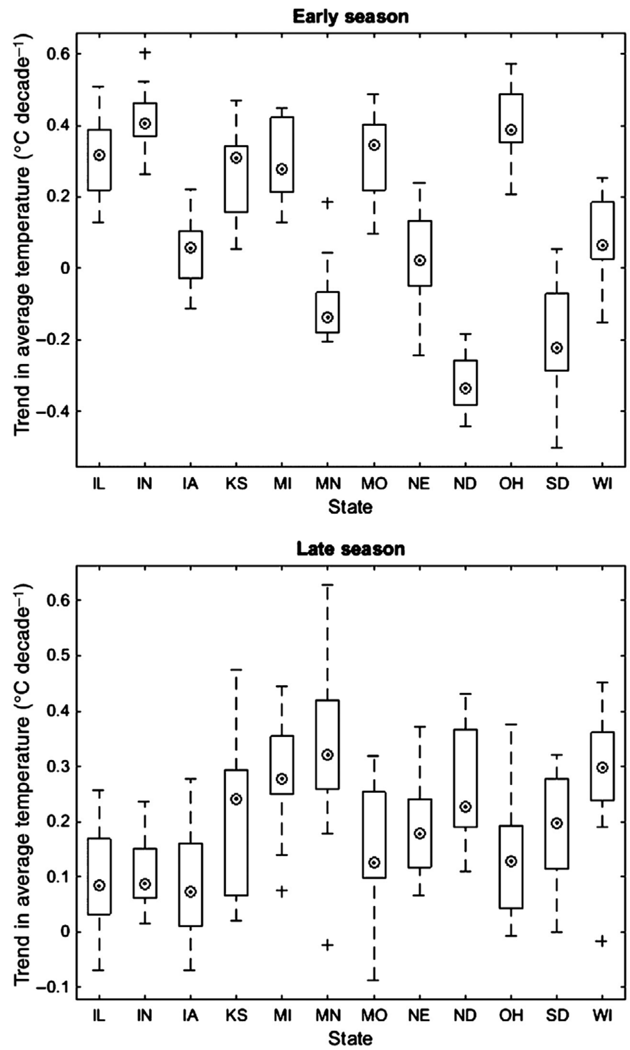

Figure 4. Box-and-whisker plots of the decadal trends in average temperature during the early season and late season from 1980 to 2013 for the locations of this study in the 12 Midwestern US states. Note: The 'central box' represents the central 50% of the data, its lower and upper boundary lines are at the first and third quartile of the data, and the central target indicates the second quartile (median) of the data. Two dashed vertical lines extending from the central box indicate the remaining data outside the central box that are not regarded as outliers. The plus signs indicate the remaining outliers. Same definitions apply in the remaining box-and-whisker plots.

3.3. Trends in precipitation

From 1980 to 2013, growing season precipitation has increased by 12.20±21.27 mm decade^{-1} for the study locations in the Midwest United States. The majority of the research locations show increasing trends in growing season precipitation, but only 4% of these are statistically significant. This result is consistent with that identified by Feng and Hu (2004), in which a wetting climate has occurred during the period 1951–2000 in the Midwest. Within the growing season, the majority of the locations are becoming wetter in the early season but drier in the late season (Figure 5). On average, early season precipitation is increasing by 16.79 mm decade^{-1} and late season precipitation is decreasing by 4.73 mm decade^{-1}. Among the 12 Midwestern states, this within-season reversing trend in precipitation is found in: Illinois, Iowa, Michigan, Minnesota, Missouri, Nebraska, North Dakota, and Wisconsin (Figure 6). In particular, the drying trend in the late season is of greater magnitude than the wetting trend in the early season for these four states: Iowa, Michigan, Minnesota, and Wisconsin. On the monthly timescale, the majority of the locations are becoming wetter in April, May, June, and October, but drier in July, August, and September (Figure 7). Overall, the greatest wetting magnitude occurs in April, when 95% of the locations are becoming wetter (11% are statistically significant, see Figure 8(a)). The greatest drying magnitude occurs in August, when 72% of the locations are becoming drier (6% are statistically significant, see Figure 8(b)).

By combining analyses of temperature and precipitation trends, we find that in May and June, weak positive trends in maximum temperature are accompanied by positive trends in precipitation. But in July, negative trend in maximum temperature is not accompanied by positive trend in precipitation. And we interpret these results as follows: in May and June, higher precipitation leads to increased recharge of deep soil moisture and increased amounts of surface evaporation. Therefore, this leads to increased crop transpiration in July by deep rooting crops like corn. The increased solar energy-partitioning to latent heat during May–July leads to (1) reduced daytime energy-partitioning to

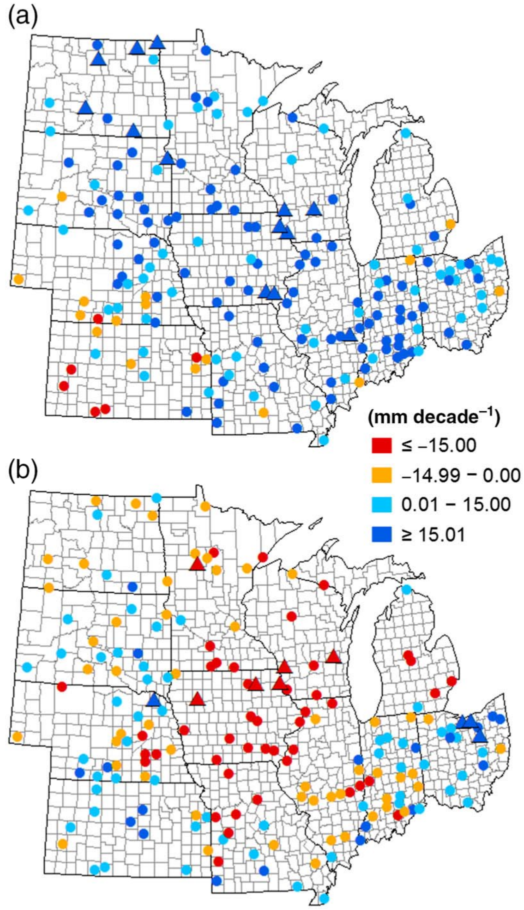

Figure 5. Geographical distribution of the decadal trends in precipitation during the (a) early season and (b) late season from 1980 to 2013 for the locations of this study.

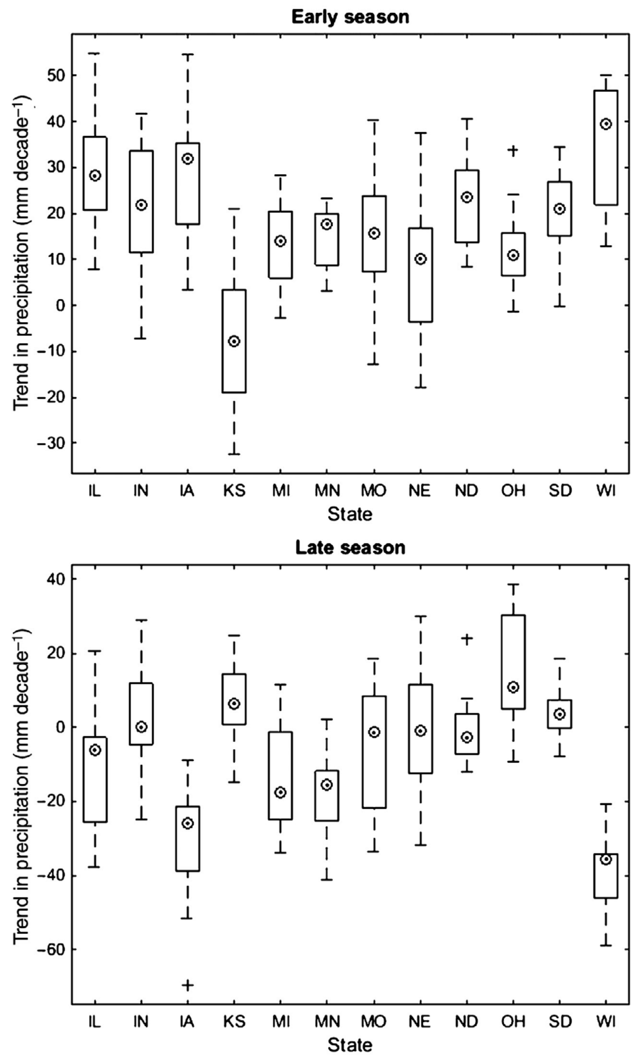

Figure 6. Box-and-whisker plots of the decadal trends in precipitation during the early season and late season from 1980 to 2013 for the locations of this study in the 12 Midwestern US states.

sensible heat (reduction of maximum temperature), (2) increase of absolute humidity (Takle, 2011) with accompanying reduction of nighttime surface longwave radiation, and hence (3) increase in minimum temperature. Item (2) may also be accompanied by increased cloudiness during May–July, which is consistent with item (3), although cloud cover data are lacking to confirm this.

The reduction of daytime maximum temperature by increased precipitation as described in the previous paragraph has substantial implication for agriculture in the region. This mechanism protects crops like corn from extreme high temperatures during the pollination period (July) and also masks a potential threat for dry years. Undesirably, if May–June precipitation is insufficient to suppress high daytime maximum temperatures in June and July, the underlying warming, evidenced by the increase in minimum temperature, will not be offset and could lead to extreme high daytime temperatures and eventually yield reductions. Take the year of 2012 as an example, the dry spring and summer in Iowa led to the hottest July since 1936 (Hillaker, 2013), and reduced corn grain yield to the lowest level since 1995 (Swoboda, 2013).

4. Summary and conclusions

Our results exhibit a high degree of spatial consistency where meteorological stations with the largest warming magnitudes in maximum and minimum temperatures during the early season and late season were generally in close proximity, and such spatial consistency relative to growing season in the Midwest United States has not been found in other climate trend studies. We conclude that an extensive warming in growing season average temperature has occurred in the Midwest United States during the most recent three decades. This regional warming is contributed more by the greater increase in growing season minimum temperature as compared with the increase in growing season maximum temperature. Within the growing season, average temperature is increasing more in the late season than in the early season. And this is because of the much greater warming magnitude in maximum temperature in the late season, especially in Minnesota, Wisconsin, and Michigan. Faster increases in maximum temperature in the late season could imply higher risks of high temperature extremes, and local agricultural producers need to address the potential risk of grain yield reduction, especially for non-irrigated sites. Both laboratory- and site-based studies have revealed the negative effects of high temperature

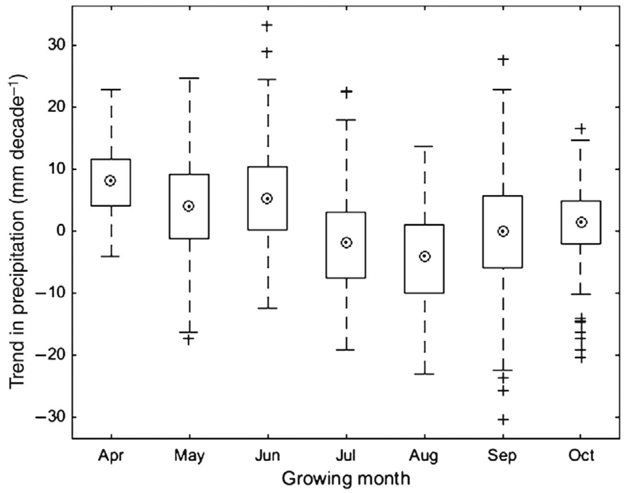

Figure 7. Box-and-whisker plot of the decadal trends in precipitation during the growing months from 1980 to 2013 for the locations of this study in the 12 Midwestern US states.

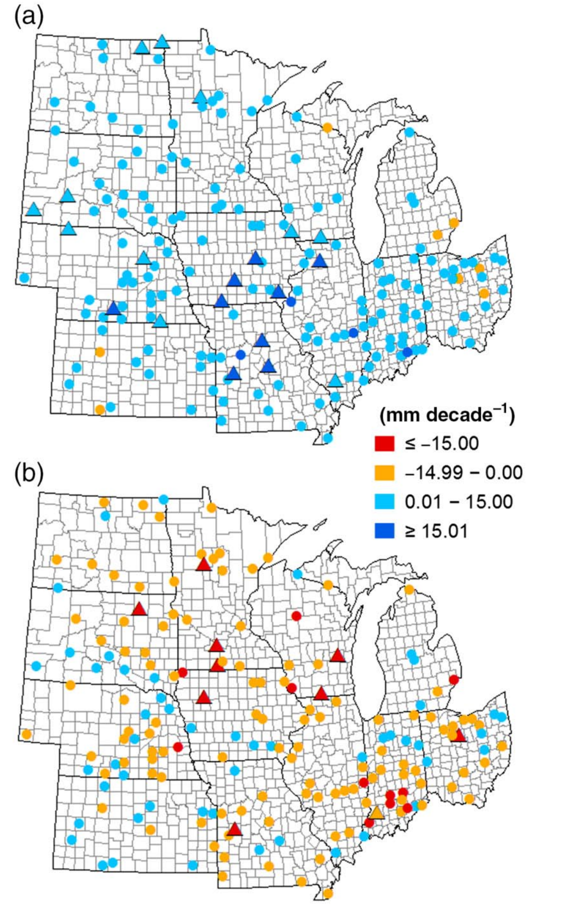

Figure 8. Geographical distribution of the decadal trends in precipitation in (a) April and (b) August from 1980 to 2013 for the locations of this study.

extremes in critical reproduction stages on corn yields, such as after pollination, between tasseling and silking, and during grain filling (Cheikh and Jones, 1994; Southworth *et al.*, 2000). During the early season, dominant trends in maximum temperature are a decrease in North Dakota, South Dakota, Minnesota, the northern parts of Nebraska and Iowa, as well as the western part of Wisconsin. Overall, minimum temperature is increasing more in the early season than in the late season. Interestingly, there is an evident spatial pattern difference for the statistically significant warming in minimum temperature during the early season and late season. In the early season, statistically significant warming in minimum temperature is focused in Missouri, Illinois, Indiana, and Ohio. But in the late season, statistically significant warming in minimum temperature is focused in North Dakota, South Dakota, and Minnesota. It is noteworthy that, decreasing or even significantly decreasing trends in early season minimum temperature are detected in the northwest part of the study region, covering the western portions of North Dakota, South Dakota, and Nebraska. This is not contrary to the climate warming, and Wolfe (2013) already stated that despite a well-documented trend for warmer winters and earlier springs across the globe, the risk of freeze damage continues. Local producers should think of the potential freeze damage when planning on earlier planting, according to Neild and Newman (1990). Poor germination resulting from below-normal temperatures rather than freezing temperatures is the greatest hazard of planting too early. On the basis of monthly analysis, we conclude that the dominant trends in average temperature are positive for all seven growing months. The greatest warming magnitude occurs in September, when maximum and minimum temperatures are increasing by 0.34 and 0.18 °C decade^{-1}, respectively. The smallest warming magnitude occurs in July, when the majority of the locations show decreasing trends in maximum temperature. Observed changes in temperature have shifted corn phenology and affected corn grain yields during 1981–2000 in China (Tao *et al.*, 2006). Increased monthly minimum temperature in May and September has been found to be significantly correlated with the increase of corn yield in Northeast China (Chen *et al.*, 2011). By contrast, Lobell and Field (2007) found a clearly negative response of global yields to increased temperatures for corn. Because of the different subregional patterns in temperature trends in the Midwest United States, we strongly suggest that further research should include crop modelling as well as statistical analysis to evaluate the impacts of temperature increases on corn grain yields. Also because the growing season minimum temperature has a greater increase than the increase in maximum temperature, the majority of the locations show decreasing trends in growing season DTR. Within the growing season, dominant trends in DTR are decreasing both in the early season and late season, and the magnitude is greater in the early season than in the late season. Dominant trends in monthly DTR show a decrease, except in September when maximum temperature has increased nearly twice as fast as minimum temperature during the study period. The greatest decreasing magnitude in monthly DTR occurs in June, when minimum temperature has increased four times as fast as maximum temperature on average.

From 1980 to 2013, we conclude that the growing season precipitation has been increasing for the majority of the locations in the Midwest United States, however, few of these wetting trends are statistically significant. It is worth noting that this wetting trend is driven by the increasing precipitation in the early season, while precipitation is decreasing in the late season. This wetter early season–drier late season phenomenon is found in 8 of the 12 Midwestern states: Illinois, Iowa, Michigan, Minnesota, Missouri, Nebraska, North Dakota, and Wisconsin. Taking Wisconsin as an extreme example, growing season precipitation is increasing during the period of 1980–2013, but early season (and late season) precipitation is increasing (and decreasing) by more than 30 mm decade^{-1} on average. Although only seven meteorological stations are used in the precipitation trend analysis in Wisconsin, the small sample size could be part of the reason for the extreme results. These results indicate some potential concern about the tendency in extreme weather events such as flood in the early season and drought in the late season. Grassini *et al.* (2009) pointed out that rainfed crops grown in the Western Corn Belt are frequently subjected to episodes of transient and unavoidable water stress, especially in the critical development stage (around and after silking). Mishra and Cherkauer (2010) found that corn yield was negatively correlated with meteorological drought during the sensitive period in late season (grain-filling period). In the north-central part of the study area, covering Minnesota, Wisconsin, and Iowa, climate has become warmer (statistically significant) and drier in late season, the combination of potential heat stress together with rainfall deficit would hurt the local corn production. Future research could focus on the precipitation indices based on finer timescales (e.g. weekly) when homogenization techniques become available. The most recent National Climate Assessment has pointed out that, in the next few decades, temperatures are projected to continue rising in the Midwest, more specifically, average temperatures are expected to increase faster in the northern part while days above 35 °C are expected to increase more in the southern part of the region (Pryor *et al.*, 2014). In addition, under the A2 scenario (higher emissions), the number of consecutive dry days is projected to increase in Nebraska and Kansas, whereas the number of heavy precipitation days is projected to increase in North Dakota and South Dakota (Shafer *et al.*, 2014). As a result, the benefits of longer growing seasons and rising CO_2 levels will be progressively offset by extreme weather events (Pryor *et al.*, 2014). Hence, we suggest further research be focused on quantifying the impacts of historical climate trends on cereal grain crop yields in the Midwest United States, in order to offer a scientific basis for the long-term adaptation strategies.

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